Proton Driver Upgrade: Physics Case

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Neutrino Oscillations are Exciting

Stunning experimental results have established that neutrinos have nonzero masses and mixings

The Standard Model cannot accommodate neutrino mass terms, which require either the existence of right-handed neutrinos → Dirac mass terms, or a violation of lepton number conservation → Majorana mass terms.

Hence this sector of the Standard Model is broken.

We know that neutrino masses and mass splittings are tiny compared to the masses of any of the other fundamental fermions. This suggests radically new physics, which perhaps originates at the GUT or Planck Scale, or indicates the existence of new spatial dimensions.

Whatever the origin of the observed neutrino masses & mixings is, it will certainly require a profound extension to our picture of the physical world.

Neutrino Mixing - 1

Within the framework of 3-flavor mixing, the 3 known flavor eigenstates (ν_e, ν_μ, ν_τ) are related to 3 neutrino mass eigenstates (ν_1, ν_2, ν_3) :

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 3\times 3 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

We know that U_{MNS} is very different from the CKM Matrix

$$\begin{pmatrix} \text{large} & \text{large} & \text{small/tiny ?} \\ \text{large} & \text{large} & \text{large} \\ \text{large} & \text{large} & \text{large} \end{pmatrix}$$

$$\begin{pmatrix} \sim 1 & \text{small} & \text{tiny} \\ \text{small} & \sim 1 & \text{tiny} \\ \text{tiny} & \text{tiny} & \sim 1 \end{pmatrix}$$

Neutrino Mixing - 2

In analogy with the CKM matrix, U_{MNS} can be parameterized using 3 mixing angles (θ_{12} , θ_{23} , θ_{13}) and one complex phase (δ) :

$$\begin{pmatrix} C_{12}C_{23} & S_{12}C_{13} & S_{13}\, e^{-i\delta} \\ -S_{12}C_{23} - C_{12}S_{23}\, S_{13}\, e^{i\delta} & C_{12}C_{23} - S_{12}C_{23}\, S_{13}\, e^{i\delta} & S_{23}C_{13} \\ S_{12}S_{23} - C_{12}C_{23}\, S_{13}\, e^{i\delta} & -C_{12}S_{23} - S_{12}C_{23}\, S_{13}\, e^{i\delta} & C_{23}C_{13} \end{pmatrix}$$

Neutrino Physics: First Round of Questions

Are there only three neutrino flavors, or do light sterile neutrinos exist? Are there any other deviations from three-flavor mixing?

There is one unmeasured angle (θ_{13}) in the mixing matrix. Is θ_{13} non-zero?

We don't know the mass-ordering of the neutrino mass eigenstates. There are two possibilities, the so-called "normal" hierarchy or the "inverted" hierarchy. Which mass hierarchy applies?

There is one complex phase (δ) in the mixing matrix accessible to ν oscillation measurements. If θ_{13} & $\sin\delta$ are non-zero there will be CP Violation in the ν-sector. Is there CP Violation in the Neutrino Sector ?

What precisely are the values of the neutrino masses? Are ν masses generated by Majorana mass terms, Dirac mass terms, or both?

The Importance of Neutrino Oscillations

The answers to these questions will guide our understanding of what lies beyond the Standard Model, and whether the new physics provides:

1. An explanation for the baryon asymmetry of the Universe (via leptogenesis)

2. Deep insight into the connection between quark and lepton properties (via Grand Unified Theories)

3. An understanding of one of the most profound questions in physics: Why are there three generations of quarks and leptons?

In addition, the answers may well further challenge our picture of the physical world, and will certainly have important implications for our understanding of cosmology and the evolution of the early Universe.

Fermilab and Neutrinos

Fermilab is host to the US accelerator-based neutrino program:

MiniBooNE: LSND oscillation test
MINOS: Long-baseline, atmospheric neutrino mass scale
MUCOOL: Neutrino Factory R&D
MIPP: (partial motivation): Particle production (ν beam systematics)
Minerva: (neutrino cross-sections)

This suite of experiments provides a cutting-edge World-class experimental program that is a key part of the Global neutrino program.

The Importance of a MW-Scale Proton Driver

The presently foreseen experimental neutrino program will be limited by statistics. To do the physics we need the most intense neutrino beams and the most massive detectors that are practical/affordable.

If $\sin^2 2\theta_{13}$ is smaller than ~0.01 the only way we know of accessing the critical oscillation physics is with a a MW-scale proton driver ($\rightarrow$ ν-Superbeam) plus a very massive detector … probably followed up by a Neutrino Factory (driven by the same MW-scale proton driver).

If $\sin^2 2\theta_{13}$ is greater than ~0.01 Superbeam experiments will be the critical neutrino oscillation experiments

In all scenarios we need Superbeams, and the rate at which we can make progress with the neutrino program will largely be determined by the time it takes to initiate a superbeam program.

A Proton Driver Based Program that Achieves the Ultimate Sensitivity

Step 1: A 2MW Proton Driver and very massive (off-axis ?) Superbeam experiment that probes $\sin^2 2\theta_{13}$ down to ~0.001-0.002 and if the result is positive, determines the mass hierarchy and begins the search for CP Violation.

Step 2: A second generation Superbeam experiment optimized to complete the first generation physics program OR a Neutrino Factory, as needed.

This will enable the full first order physics program to be completed if $\sin^2 2\theta_{13}$ exceeds $O(10^{-4})$.

Oscillation Physics Reach

Beam Name	Mass (kton)	Power (MW)	$\sin^2 2\theta_{13}$ sens.[a]	δ[b] CPV	Mass Hierarchy
OPERA[o]	1.8	0.15	0.04	-	-
ICARUS[o]	2.4	0.15	0.03	-	-
MINOS[m]	5	$0.25 \rightarrow 0.4$	0.05	-	-
CNGS**	2.35	.15	~ 0.02**		-
T2K	22.5	0.8	0.006	-	-
NOνA	50	0.4	0.004	-	Yes
T2HK	450	4	~ 0.001[s]	$\lvert\delta\rvert > 20°$	-
Super-NOνA	100	2	~ 0.001[s]	135 ± 20	Yes
BNL2NUSL	500	1	0.004	45 ± 20	Yes!
CERN SPL	400	4	0.0016	90 ± 30	-
β Beam	400	.04		T viol.	-
ν Factory	50	4	$< 10^{-4}$	90 ± 20	Yes

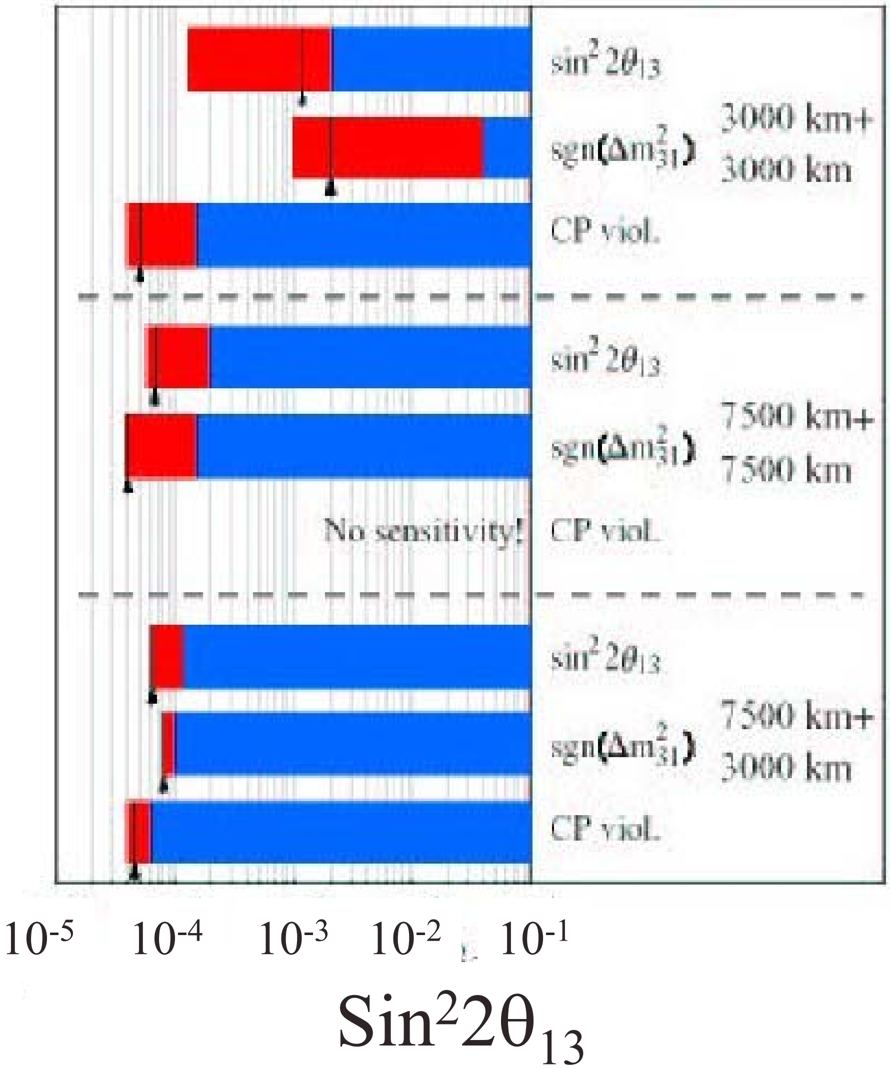
[a] at $\Delta m^2_{32} = 3 \times 10^{-3} eV^2$, at $90\% CL$
[b] all evaluated at different regions of parameter space!
[o] Komatsu, Migliozzi, Terranova J.Phys.**G29** 443, 2003 [m] Diwan, Messier, Viren, L.Wai, NUMI-L-714
[s] Assume 5% systematic uncertainty!
**modified, Rubbia, Sala, hep-ph/0207084

Near-term program: no sensitivity to CPV or mass hierarchy (matter effects)

Superbeam program: order of magnitude improved θ_{13} sensitivity, & increasing chance of observing CPV & mass hierarchy.

Superbeams open the way to the ultimate neutrino factory sensitivity

A MW-Scale Proton Driver provides a path to the Ultimate Neutrino Oscillation Physics Reach at a Neutrino Factory



The full physics program (Establishing the magnitude of θ_{13}, determining the mass hierarchy, & searching for CP Violation) can be accomplished provided $\mathrm{Sin}^2 2\theta_{13} > O(10^{-4})$!

The Broader Neutrino Program

The Booster-Based ν Program is limited by proton economics and this will get worse when the NuMI program begins.

An upgraded proton driver will provide flexibility to exploit big surprises (for example, a positive MiniBooNE result) ….

… and opportunities for new "small" neutrino experiments.
Examples: low energy neutrino cross-section measurements, neutrino magnetic moment and exotic interaction searches.

The neutrino program that could be supported by a 2MW proton driver is likely to consist of a multi-phase program with at least a handful of experiments that provide world class cutting edge physics for a period of a couple of decades or longer.

A Broader Proton Driver Program

(I believe) neutrino physics provides a compelling case for a 2MW proton driver, but diversity is also important. With an intensity frontier machine there are other potentially big discovery type experiments, and important measurements, to chose from:

Probes of Lepton Flavor Violation: $\mu \rightarrow e\gamma$, $\mu \rightarrow e$ conversion

Precision tests & measurements of the CKM Matrix: Comparison of B-physics measurements and rare kaon decay measurements, and the search for CP-Violation in the hyperon system.

Interface between particle & nuclear physics: Flavor-dependent and polarized nucleon structure functions, search for exotic hadrons, nuclear shadowing, pion structure function.

Physics Study

The previous proton driver study in 2001 included a physics study that produced a 134 page report $\rightarrow$ good starting point.

We need to update and extend the study, look more at how the expected physics capabilities change with proton driver performance, and produce the documentation needed for the next step.

We are in the middle of putting together an organization to accomplish this, with working groups to cover the various physics sub-topics, and a workshop in the Fall.

Physics Study – Organization

Local Organizing Group

Steve Brice
Harry Cheung
Dave Christian
Kieth Ellis
Steve Geer (chair)
Debbie Harris
Penny Kasper
Jorge Morfin
Hogan Nguyen
Stephen Parke
Ron Ray

Tentative Working Group List

Accelerator-Based Neutrino Oscillation Physics
Neutrino Interaction Physics
Low Energy & Stopped Muon Program
Kaons and Pions Antiprotons
Neutrons
Electrons (?)
Accelerator-Based Particle Astrophysics (?)
B- and C- Physics

Summary

A 2MW proton driver at Fermilab would provide, for decades to come, an exciting World Class physics program for the laboratory and its user community.

Neutrino oscillation physics would provide the main thrust for the program, but the proton driver can also support a more diverse program of world class experiments.

The details need further exploration and the case needs to be well documented to enable us to proceed to the next step … this is the purpose of the physics study.